

UNCLASSIFIED

Defense Technical Information Center Compilation Part Notice

ADP011122

TITLE: Use of ATTAS for ACT Research

DISTRIBUTION: Approved for public release, distribution unlimited

This paper is part of the following report:

TITLE: Active Control Technology for Enhanced Performance Operational Capabilities of Military Aircraft, Land Vehicles and Sea Vehicles
[Technologies des systemes a commandes actives pour l'amelioration des performances operationnelles des aeronefs militaires, des vehicules terrestres et des vehicules maritimes]

To order the complete compilation report, use: ADA395700

The component part is provided here to allow users access to individually authored sections of proceedings, annals, symposia, etc. However, the component should be considered within the context of the overall compilation report and not as a stand-alone technical report.

The following component part numbers comprise the compilation report:

ADP011101 thru ADP011178

UNCLASSIFIED

Use of ATTAS for ACT Research

J.-Michael Bauschat

Gunnar Duus

Klaus-Uwe Hahn

Wieland Heine

Dehlia Willemssen

Deutsches Zentrum für Luft- und Raumfahrt e.V.

Institut für Flugsystemtechnik

Lilienthalplatz 7, D-38108 Braunschweig, Germany

www.fm.bs.dlr.de/flugsystemtechnik

Summary

The application of active control technologies (ACT) has a potential to enhance the operational performance capabilities of aircraft. In particular the introduction of digital computers with today's processing power allows to think about more and more complex and/or unconventional control schemes for more efficient operation of aircraft. For the final validation and verification of new approaches the flight test is the ultimate test for concept demonstration under real world conditions. For this purpose DLR uses its flying testbed ATTAS (Advanced Technologies Testing Aircraft System) which is ideally suited due to its unique configuration. ATTAS is configured to meet the requirements of a variety of applications by freely programmable functions and interface capabilities to link customer soft- and hardware.

This paper summarises the recent and current projects and research activities relevant for ACT in which flight testing using ATTAS is an important factor.

Introduction

The use of modern flight control systems offers several improvements such as increased manoeuvrability, performance and flight safety as well as a reduced workload. The development, optimisation and investigation of advanced ideas requires precise system modelling of the augmented aircraft. This includes the application of non-linear simulation techniques for extensive system analyses.

In the future, a manipulation of the wing shape in order to optimise the aerodynamic characteristics will be used. This is often referred to as "smart wing". One rather basic example of this technique is the use of special flaps – the so-called direct lift control (DLC) – to simulate dynamic properties of other aircraft as it is done on ATTAS (see below). This also requires the use of sophisticated flight control systems.

In this paper the following programs are described. All of them deal with modern control laws and involve flight testing on ATTAS. The SAFIR project investigated control laws for a small transport aircraft and included aspects such as dissimilar software and mode transients. The European REAL project aims at establishing a more efficient approach for the design of autopilot systems of civil airliners. The proposed controllers will be flight tested on ATTAS. In order to validate a new criterion for the prediction of adverse aircraft-pilot coupling problems due to rate limitations in the flight control system the SCARLET3 program was conducted. In the ARCORE project unconventional control schemes (such as differential thrust for yaw control) and different reconfiguration strategies (in case of control surfaces failures) were examined and flight tested. To familiarise pilots with different control schemes in a safe but realistic environment the in-flight simulation capabilities of ATTAS can be used as was recently done for the French test pilot school E.P.N.E.R. ATTAS is also used for investigating the possible benefits of an active sidestick with force feedback that has been developed by DLR and TU Braunschweig.

Test aircraft ATTAS

DLR's flying testbed ATTAS (Advanced Technologies Testing Aircraft System, figure 1) is based on a VFW 614 civil transport aircraft (44 passengers, twin turbofan, short haul) that was modified to serve as an in-flight simulator and technology demonstrator. Modifications include the fly-by-wire/light flight control system, the in-flight simulation architecture (explicit model following system), complete flight test instrumentation, as well as data acquisition and recording. ATTAS is configured to meet the requirements of a variety of applications by freely programmable functions and interface capabilities to link customer soft- and hardware. The aircraft is primarily used for DLR's research in the fields of flight control, flight guidance, flying qualities, and man-machine interfacing.¹



Fig. 1: DLR's flying testbed ATTAS

Programs

In this section the projects mentioned above are described more in detail.

SAFIR

With regard to the development of the Aerospace Technologies Demonstrator aircraft by DaimlerChrysler Aerospace (Dasa) Airbus new control laws for electrical flight control systems have been tested on ATTAS. In the SAFIR project (Small Airliner Flight Control Laws Investigation and Refinement), for the first time in Germany, this kind of manual flight control laws (FCLs) for small future civil transport type aircraft have been flight tested by a joint team from Dasa Airbus and DLR Institut für Flugsystemtechnik.^{2,3}

The demand for modern electronic primary flight control systems in small transport aircraft (100 seater) formulates the need for new cost-effective concepts providing familiar standard control functions based on proven techniques that are accepted by the certification authorities. In the frame of a technology program for an electronic flight control system control laws have been developed by Dasa to cope with these challenges. The SAFIR project aimed at the validation, demonstration, and evaluation of the flight control laws by a flight test program. In April 1993 Dasa and DLR launched this project. Already half a year later the first flight test on ATTAS was carried out.²

Flight Control Laws

The investigated FCLs provide normal laws with different modes and various envelope protections (see figure 2). The protections prevent certain boundaries from being exceeded. For the operation of the normal laws numerous signals need to be measured, consolidated, processed, and fed back. In case of any system failure affecting adversely the correct operation of the normal laws a system degradation to the direct laws takes

place. The direct laws link the inceptors directly to the control surfaces by fixed gains simply providing feed-forward control.

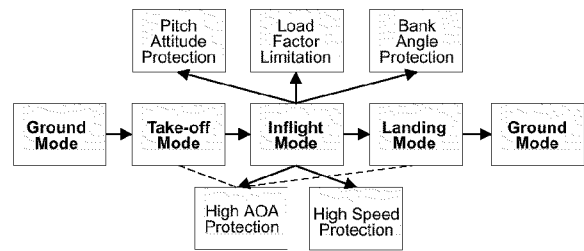


Fig. 2: Modes of the Normal Flight Control Laws³

Development Process

The FCLs were designed by Dasa using their Computer Aided Software Engineering (CASE) tool HOSTESS (High Order Structuring Tool for Embedded System Software) which provides a user interface on a graphical block diagram level.⁴ This tool offers standardised software specification, automated coding process, automatic checks and testing, improved software documentation, and facilitated configuration management.

The optimisation of the FCLs was done in an iterative process over different loops illustrated by Figure 3. After the careful design of the FCLs using Dasa's Development Flight Simulator they were adapted to ATTAS in the ATTAS System Simulator. The latter provides the identical data processing environment as available on board the test aircraft. If any modification of the software was required from this checkout HOSTESS quickly produced the new code. After having successfully passed the final check in the ATTAS System Simulator the FCL software was qualified for test flight by a revision mark.

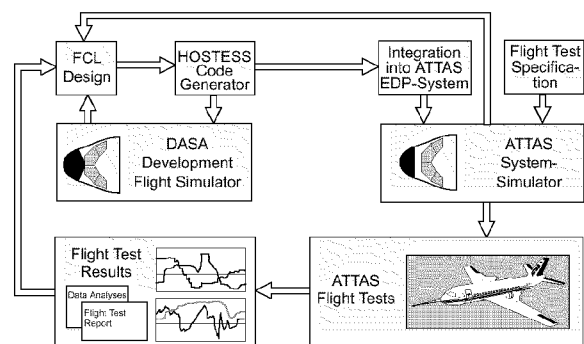


Fig. 3: Flight Control Law Development Process

The ATTAS system simulator was also used for the pilot's familiarisation with the current version of the FCL, for flight program optimisation, and training of the test procedures. This

includes the final design of test sequences and their arrangement for flight. Each flight sequence was precisely defined on a flight test card. The order of the test cards determined the course of the respective flight experiment.

Flight Te

The SAFIR project was separated into two phases. In the first phase (SAFIR 1) the FCL software was organised in an independent subroutine which was completely transferred into ATTAS' Experiment and Control Computer (ERR, see figure 4). The data processing system supplied the required data to the FCL functions via an experiment-specific software interface. This included continuous stream data like sensor signals as well as artificially generated information only needed to satisfy the FCL inputs. The output of the FCLs were again transferred via the interface to fill the vector of control variables in the ATTAS data processing system directly stimulating the control surfaces. This first campaign, SAFIR 1, aimed at evaluating the functionality and the performance of the FCLs within the whole flight envelope. Mainly the correct function and the handling qualities of the normal laws (including flight envelope protections that prevent critical flight conditions) have been investigated.²

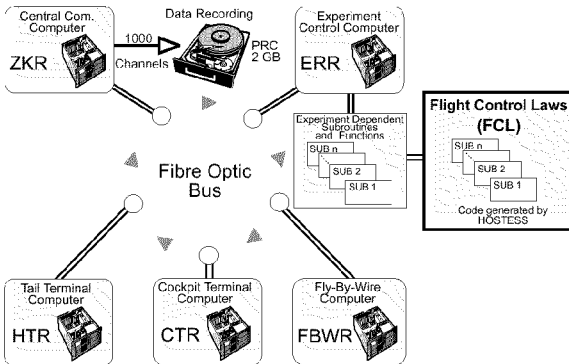


Fig. 4: Experiment Configuration of SAFIR 1

The second phase (SAFIR 2) focused on system relevant aspects.³ Two dissimilar versions of the FCLs (in FORTRAN and ADA) were created to be implemented in a command and a monitor lane hosted by the high performance Flight Control Law Computer (FCLC). This FCLC had been installed on-board ATTAS for SAFIR 2 and was connected to the data processing system via the Central Communication Computer (ZKR) as illustrated in figure 5.

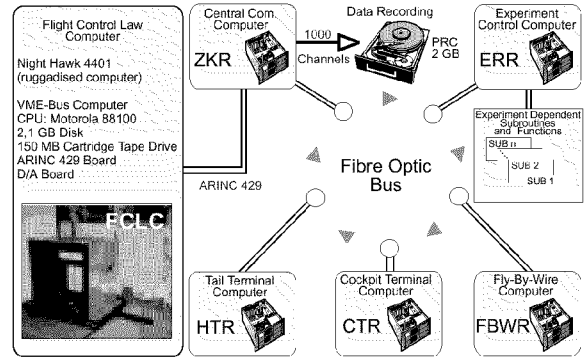


Fig. 5: Experiment Configuration of SAFIR 2

Special control inputs and flight tasks to validate the functionality of the FCLs throughout the entire flight envelope including the protections have been designed. The generic signals that have been used in this phase mainly consisted of precisely defined manually and artificially generated sidestick, pedal, and thrust lever inputs to stimulate the aircraft dynamics and to check the correct operation of the FCLs. For handling qualities investigations a specific manoeuvre was designed composed of combined movements in the horizontal and vertical plane (see figure 6). Pilot questionnaires have been developed asking for Cooper-Harper ratings for the different task sequences. The FCL performance in normal airline operation was investigated with typical manoeuvres like synthetic ILS approaches (ILS artificially generated by the ATTAS computer system on "push button" demand), turns and heading changes during (step) climb/decent manoeuvres.

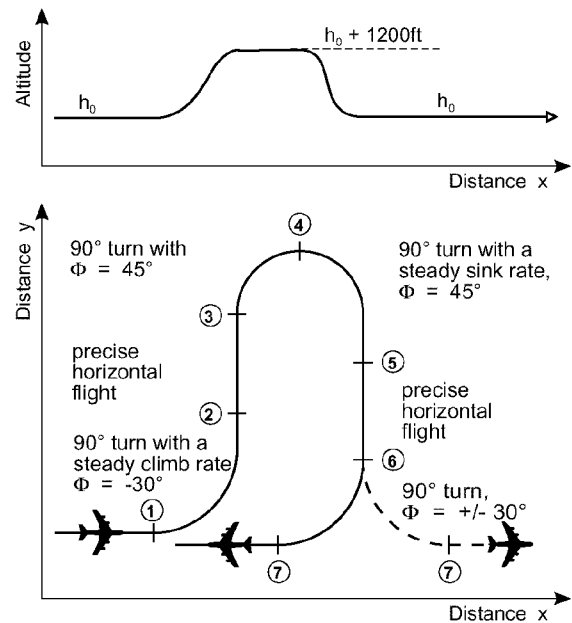


Fig. 6: SAFIR Manoeuvre

Conscientious briefings and debriefings completed the flight test approach.

Results

During the SAFIR project a very effective and well organised infrastructure has been built up between Dasa and DLR. The FCLs were thoroughly validated and successfully demonstrated by a comprehensive flight test program. Within the period from 1993 to 1996 more than 300 single test sequences were carried out with different test and airline pilots. The total flight time for the 12 test flights of the whole project was 32 hours. Altogether 9 different software versions with 110 modifications have been tested.

Due to the dedicated flight data processing system and the well trained flight test team a first analysis was possible a few hours after flight. The flight test results showed high precision of the FCL performance with respect to the requirements.

This is illustrated in figure 7. It shows the results of a dynamic pitch manoeuvre where the pilot applied full stick back. Although this step input to the pitch axis at $V_{CAS} = 180$ kts results in high pitch attitudes of more than 22° (and additional loads of 0.8g) the AOA protection is able to prevent the aircraft from exceeding the maximum angle of attack α_{lim} .

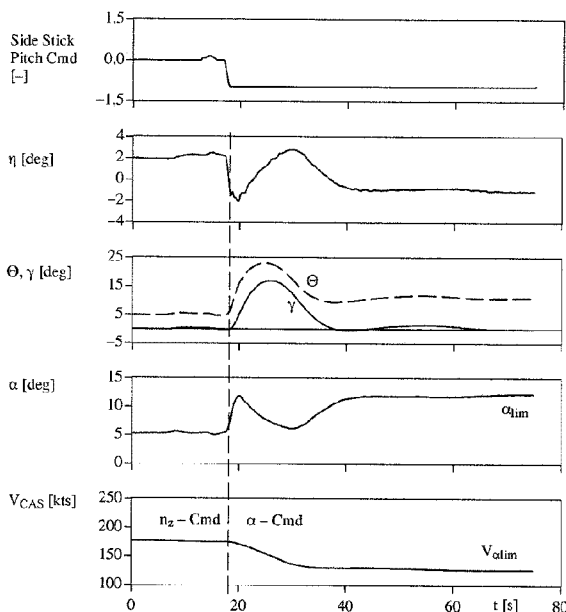


Fig. 7: High AOA Protection³

Equally good results have been achieved for the other protections. The handling qualities for airline typical operations were rated Level 1.

Due to careful preparation the flight tests were highly efficient. Because of the comprehensive on-board equipment and the safety pilot concept ATTAS is ideally suited to serve as an FBW (fly-by-wire) platform for flight testing of (uncertified) flight control soft- and/or hardware. Supported by a small but well trained team ATTAS provides the capability to perform experiments in a real world environment (weather effects, sensor characteristics and quality, operational conditions with pilot-in-the-loop etc.) with short term preparation and at low cost and low risk.

REAL

Today's development process for autopilot systems contains a time-consuming trial-and-error approach. This is especially true for automatic landing, which should be robust against a large number of parameters, like runway characteristics, weather and aircraft uncertainties. Modern robust design methods offer ways to handle such uncertainties and parameter variations in a structured manner, see e.g. contributions to Ref. 5. It is therefore interesting to know whether these methods offer the possibility to improve the design process of autopilot systems and to avoid trial-and-error practices. The central question to be answered in the REAL (Robust and Efficient Autopilot control Laws design) project thus is: "How can advanced design and synthesis methods contribute to a more efficient design process of robust controllers for CAT III autoland systems of civil airliners?". The REAL project is carried out under a contract awarded by the Commission of the European Communities as part of the 4th Brite/EURAM Frame Work Programme, and started in May 1998. The partners are from France (Aerospatiale Matra Airbus, ONERA), Germany (DaimlerChrysler Aerospace Airbus, DLR) and the Netherlands (Delft University of Technology, NLR).

Controller Design

Two design teams will propose a design process including a modern design method. One design team will use multi-model/multi-objective optimisation based synthesis⁶ in combination with Dynamic Inversion⁷ and the Total Energy Control System (TECS).⁸ The other design team will apply multi-model eigenstructure assignment⁶ to the design problem. Both design teams will develop two autoland control laws. First an autoland for a generic civil transport aircraft is designed. This phase results in a design process, which is further tested via a rapid design of an autoland for ATTAS. The project scheme is summarised in figure 8.

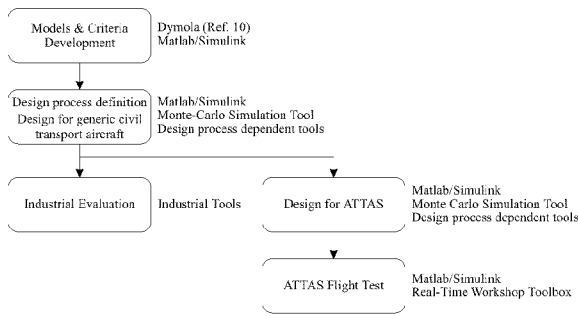


Fig. 8: Overview of the REAL project with the specified tools

For both designs, process criteria and design criteria have been defined. The main criterion for the design process is that it should cover the uncertainties and varying parameters from the beginning of the design. Another major criterion is that the process should offer a large potential for automation. The design requirements are basically the performance requirements of the Joint Aviation Requirements – All Weather Operations (JAR-AWO).⁹ These requirements will be specifically tested for by the industrial partners of the project using Monte-Carlo simulation techniques. One product resulting from the project, apart from the design processes, is a Matlab-based Monte-Carlo simulation tool. With this tool each uncertain or varying parameter like terrain slope, runway elevation, wind conditions, etc., is varied according to a selectable probability distribution during a Monte-Carlo simulation run. The outcome of the simulations is statistically evaluated, resulting in histograms and cumulative probability distributions of e.g. the longitudinal touchdown point. Using this tool the design teams are able to test their designs before sending it to the industrial partners for evaluation.

Flight Test

The ATTAS autoland systems from both design teams will also be flight tested on ATTAS. Since the designs are made in the Matlab/Simulink environment, they can be quickly transferred into C-code using Matlab's Real-Time Workshop Toolbox. This code can be implemented on ATTAS' experiment computer.

Before performing a full automatic landing, the controllers will be tested, first in the simulator and then via landings on a virtual runway in about 200-300 ft radio altitude. After positive result of the tests, one or more landings on a real runway will be performed. Via the flight tests it is examined, whether the proposed design processes result in implementable autoland controllers with sufficient performance. The flight test phase of the project is planned for the summer of 2000.

SCARLET 3

Rate limiting in modern flight control systems is the main contributor to the triggering of Pilot-in-the-Loop Oscillations (PIO).^{11,12} A new criterion capable of predicting non-linear PIO problems due to rate saturation had been developed at DLR. It is based on the location of the Open Loop Onset Point (OLOP) of the rate limiter in the Nichols chart. An OLOP location above the boundary indicates a danger of PIO problems due to rate limiting. The OLOP criterion has been validated on the basis of several PIO prone aircraft models, and recently new experiments utilising a three degree-of-freedom motion-base research flight simulator have been conducted and analysed.¹³⁻¹⁷

To continue the OLOP validation, especially to gain more experience in the pitch axis, to apply OLOP to a different aircraft type (all configurations flown in the ground-based simulator were fighters), and to examine a phase compensating rate limiter an in-flight experiment with ATTAS was conducted. A secondary goal was to test the automatic code generation tool Real-Time Workshop (RTW) for Matlab/Simulink, which had recently been installed and configured for use with ATTAS. This section describes the design, conduction and results of that experiment. The project name stands for **Saturated Command And Rate Limited Elevator Time delay**, part 3, and has been chosen to show continuity with previous work in this field at the institute.

Controller Design

It was decided not to perform an in-flight simulation of another aircraft but to fly the ATTAS base aircraft. To obtain different configurations, simple controllers with multiple gain settings were defined. For the longitudinal axis a simple n_r law was implemented. This has been modified for the second flight in order to further increase the PIO potential. For the lateral axis, a very elementary structure was used, consisting only of roll and yaw rate feedbacks to increase the damping (figure 9). For both the longitudinal and the lateral control laws a rate limiter was integrated into the controller structure. Also in the second flight, a phase compensating rate limiter taken from Ref. 18 will be used. This element is supposed to diminish the negative effects of the rate limiting.

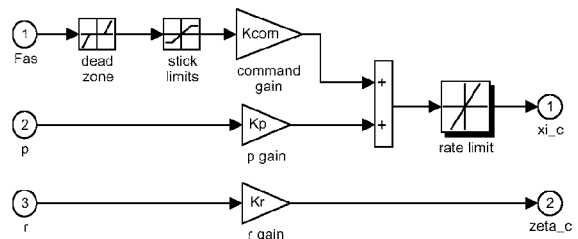


Fig. 9: Lateral controller structure

In each axis, two configurations were defined. Controller 1 used high feedback gains and was expected to exhibit good linear behavior (Level 1) but to have stronger problems after rate limit onset. Controller 2 had lower gains and was expected to have somewhat worse handling qualities in the linear case (Level 2 or 3) but to have a lower PIO potential in the non-linear rate limiting situation (known as Category II PIO).

The design of the controllers was assisted by evaluating the configurations with linear numerical handling qualities criteria such as Neal/Smith, phase rate and C^* as well as the non-linear OLOP criterion.

For comparison, also the original ATTAS direct mode (direct link between stick and surface) was investigated in combination with the actuator rate limiter that had been integrated during ATTAS' flight envelope extension to landing capability in fly-by-wire mode.

For the application of the OLOP criterion a simple gain pilot model is needed. For the design of the controllers, gains corresponding to crossover phase angles of $\Phi_{cr} = -130$ deg (longitudinal) and $\Phi_{cr} = -140$ deg (lateral) were used, respectively. These values had been selected based on previous experience. As it turned out, the gains actually applied by the pilots were lower (see below). The OLOP locations for the selected configurations are shown in figure 10. The numbers indicate the rate limit in deg/s. The bold line represents the boundary, all points above that line are predicted to be PIO prone due to the rate limitation.

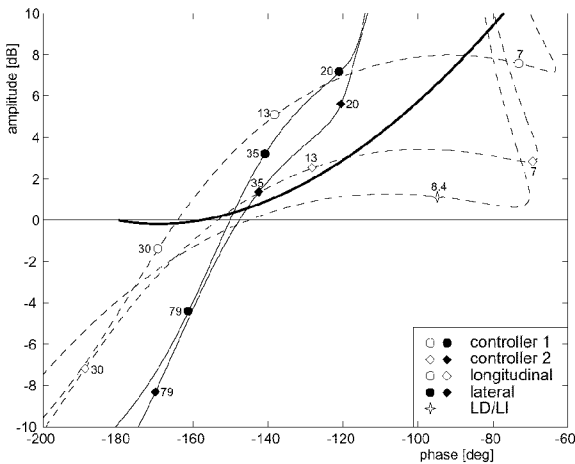


Fig. 10: OLOP locations as designed

As intended, controller 1 for both axes shows a greater Cat. II PIO potential than controller 2. The differences in the lateral axis are relatively small, though. The longitudinal direct mode configuration LD/LI is not Cat. II PIO prone, as is the lateral direct mode configuration whose OLOP lies outside the plotting range (bottom left corner).

Task

The pilot task was to follow a command attitude that was displayed on the primary flight display. A random selection of several predefined sequences was made via the switchboard on the experiment operating panel. A typical pitch sequence can be seen in figure 11. The roll command was similar but used larger amplitudes.

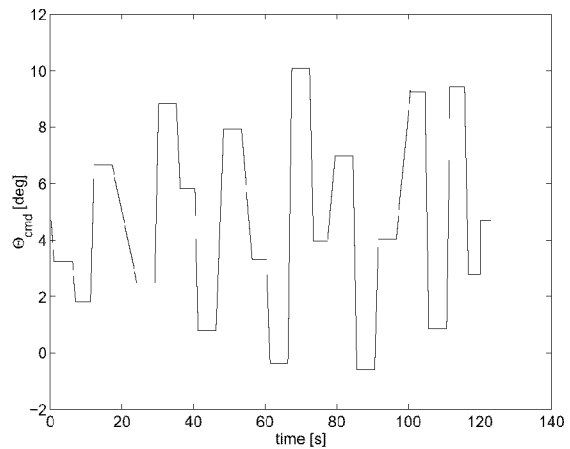


Fig. 11: Typical task sequence (pitch axis)

Conduction

All controllers were designed in Matlab/Simulink and transferred to ATTAS using Real-Time Workshop (RTW). Since in this experiment RTW was used for the first time to transfer Simulink-designed controllers to ATTAS some additional checks were performed to ensure that the automatic code generation worked as expected. As mandatory for ATTAS experiments, all configurations were tested prior to the flight in the ATTAS ground simulator. The data recorded during these tests was compared to Simulink results obtained by feeding the pilot stick input into the Simulink model (open loop) that had been used for the design of the control laws. All RTW related problems were corrected such that finally, the RTW code represented the intended Simulink model.

Results

A Cat. II PIO occurred only once, other cases with bad PIO ratings are due to linear issues. Although the task was designed for activation of the limiters this did only happen very rarely. It seems to be very difficult to get into Cat. II PIO with a stable aircraft. This was also observed in the HAVE LIMITS program,¹⁹ where Cat. II PIO only occurred for extremely low rates.

Pilot model identification

As mentioned before, for the evaluation of the OLOP criterion a simple gain pilot model is required. The well defined tracking task allowed an identification of the pilot behaviour since the input and output signals of the human pilots were available. The same iterative method as described in Ref. 9 was used to obtain a suitable pilot model gain, which represents the real pilot behavior as closely as possible (see Refs. 15 or 17 for details). With these gains, each run can be located in the OLOP diagram.

The most important result is that the gains were lower than assumed. They corresponded to crossover phase angles of approx. -100 deg (longitudinal) and -120 deg (lateral). Therefore, only one of the cases that were designed to be Cat. II PIO prone actually exhibited PIO tendencies due to the rate limit. It has to be noted that not all cases could be flown and that, in the longitudinal axis, the sensitivity to changes of pilot gain is rather low, such that an inaccuracy in determining the gain does not significantly change the OLOP location.

OLOP evaluation

For the validation of the OLOP criterion the differences between the PIO ratings of non-linear (with rate limiting) and linear (w/o rate limiting) runs have to be considered because OLOP only predicts possible problems due to rate saturation. As in previous evaluations, the following parameter was used:

$$\text{DPIOR} = \text{PIOR}_{\text{non-linear}} - \text{PIOR}_{\text{linear}}$$

Since no really linear configurations were present in this experiment, the highest rate was used instead. This is justified by the fact that the limiters were not activated for the high-rate cases. For the direct mode cases such an evaluation is not possible since no linear configuration is available. This will be done in the second flight. Figure 12 shows the results, the numbers indicate the DPIOR value.

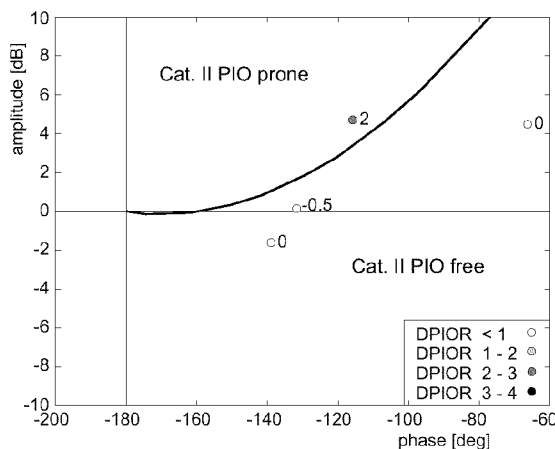


Fig. 12: OLOP evaluation

As can be seen from figure 12, only one configuration suffered from the limitation. Its OLOP is located in the critical area, whereas all other points are located in the non-critical area. This is also the only case where the limiter was significantly activated.

A second flight will be performed to add more configurations and to correct all shortcomings of the first flight. The results will be published in Ref. 20.

ARCORE

In the past numerous reconfiguration techniques have been published and discussed. Each of these techniques, like gain scheduling or online redesign, has advantages and disadvantages regarding speed, safety, accuracy, flexibility, complexity, etc. The ARCORE (Artificial Redundancy Concept for Reconfiguration) project examined two reconfiguration strategies that enhance aircraft performance after severe actuator failures.

The first strategy, the so-called two-step approach, tries to reconfigure the control system facing time constraints and uncertain failure information. Due to the fact that most modern combat aircraft have little time to adjust themselves to a severe failure in the control system it makes sense to split reconfiguration tasks into those that are time-critical and those that are not.

The second strategy puts its emphasis on adding simple reconfiguration rules to existing control systems in order to reduce costs and complexity. This so-called modular approach focuses on specific failure cases like jammed actuators and specific manoeuvres like the landing approach.

Two-Step Approach

It is obvious that a combination of different techniques might be a successful strategy to improve the overall performance of a single reconfiguration technique.

The two-step approach tries to separate reconfiguration tasks that have to be done very quickly to maintain stability and controllability from tasks that try to improve handling qualities and performance of the aircraft in a slower but more sophisticated way (figure 13).

Fast knowledge based restructuring and additional online optimisation of the control parameters combines good reconfiguration speed and proper handling of failure information affected with uncertainties.

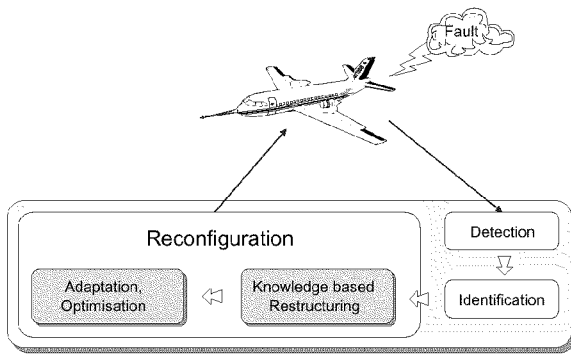


Fig. 13: Two-Step Approach

FAST

The first step of this two-step approach is the **Fault Accommodation by Structure Tuning (FAST)**. The restructuring of the controller depends on predefined control input structures and gains. The restructuring is based on the application of the control mixer concept using the pseudo-inverse to calculate the necessary inputs. As a prerequisite the control input matrix has to be known.

Two ATTAS experiments with elevators jammed in trim position have been conducted. In the first experiment the pilot was asked to use the stabiliser trim button instead of the side-stick to follow a given altitude profile with constant airspeed. While maintaining airspeed he encountered severe problems stabilising the phugoid mode with the slow stabiliser.

In the second experiment, the pilot used the side-stick and the old control law to command the aircraft after a control system reconfiguration. The reconfigured control system transforms his command, formerly sent to the elevator, into equivalent commands for the stabiliser trying to produce the same pitching moment. As a result, the reconfigured control system enables the pilot to fulfil his task much more accurately.

GRACE

Due to the large number of possible actuator failures and their numerous combinations an online adaptation period seems to be necessary as a second step to cover the often unknown impact on the control system. Especially in case of uncertain or missing failure information an optimisation technique can be applied to improve the overall performance of the damaged aircraft.

A **Genetic Reconfiguration Algorithm for Control system Enhancement (GRACE)** has been developed to solve the adaptation problem. The reason for favouring evolutionary algorithms for optimisation is mainly that they produce near-optimal solutions very reliably in case of calculus-unfriendly

cost functions or other difficult search regimes. Genetic algorithms (GA) successfully apply the principles of natural evolution, i.e. selection, recombination, and mutation, to mathematical and technical optimisation problems.^{21,22}

GRACE was tested in simulation and flight experiments. Tracking tasks with an unpredicted elevator effectiveness reduction of fifty percent have been investigated. The feed-forward parameters of an explicit model following control system were continuously adjusted and the flight test results demonstrate a significant reduction in pitch tracking error (see figure 14). Elevator effectiveness degradation starts at zero seconds.

Only the feed-forward parameters of the control system were adjusted online by the adaptation algorithm to avoid stability problems. The adaptation period lasted nearly 25 seconds due to the significant computational effort and the relatively small available computer power (ROLM HAWK/32).

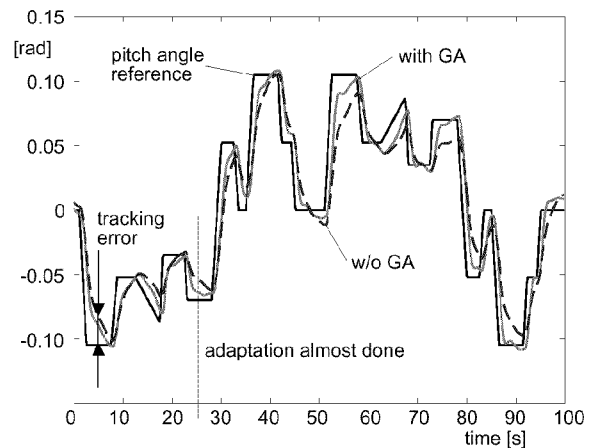


Fig. 14: GRACE Flight Test Result (tracking task with degraded elevator performance)

Since genetic algorithms are well suited for parallel processing a transputer network has been designed and connected to ATTAS' onboard FBW-system. The parallel processing almost halved the adaptation period while retaining the same accuracy.

However, the growing computational burden for covering additional failure cases and the necessary certification effort make it unlikely to combine genetic online optimisation with current control law design requirements – despite the fact that evolutionary algorithms usually provide near-optimum solutions very reliably. In addition, benefits of online optimisation might be small in cases where sufficient failure information is already available or maybe easier to procure.

Modular Approach

Important factors to influence the design process are costs, certification aspects, and the experience of the design team. With good reason modifying existing control systems instead of creating new structures and control laws is common practice in control system design. The objective of the modular approach is to use a given control system and to add a reconfiguration block, changing the existing control laws as little as possible. The development of an augmented thrust-only flight control system by NASA is a good example of that approach.²³

In the following example a total loss of hydraulic pressure is assumed. All primary control surfaces, i.e. elevator, aileron, and rudder, are no longer available. The landing gear is lowered and the flaps remain locked. The only available controls are the two engines and the electrically driven stabiliser. This failure scenario represents a severe emergency situation with little controllability left. Pitch moments can only be controlled by very slow stabiliser deflections with a rate limitation of 0.25 deg/s. Yawing motion can be controlled by means of differential thrust and roll moments via the relatively small dihedral effect also involving differential thrust. Normal symmetric thrust is used for speed and flight path angle changes.

The original control system and the flight evaluation task used in this example were derived from the RCAM (Research Civil Aircraft Model) design challenge with modifications regarding the aircraft model and the failure conditions.²⁴

To check the control system logic and to make the challenge more realistic, an evaluation trajectory was designed to reflect typical phases during approach and landing (figure 15).

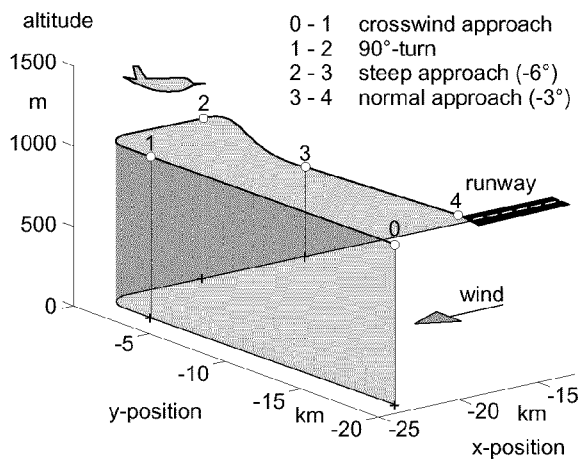


Fig. 15: RCAM Trajectory

The main controller architecture has not been changed in accordance with the main objective of the modular approach.

The modified RCAM problem uses the same disturbances like wind, gust, and wind shear as the original one. The choice of a trajectory as an evaluation criterion makes the evaluation independent of controller structure and design methodology and clearly illustrates the achieved accuracy. The most important modifications to the design challenge concern the failure conditions, the aircraft model used and the extension of the trajectory to the ground. Instead of the linear aerodynamics of RCAM a non-linear six degrees-of-freedom model of ATTAS was used. It features e.g. non-linear engine and actuator dynamics as well as the ground effect. The additional failure scenario includes a sudden loss of the control power of all primary control surfaces with normal engine behaviour left.

Reconfiguration Module

In order to overcome the severe control problem for this failure case a reconfiguration block is added to the normal control laws (figure 16). Only minor changes to the normal control laws were necessary.

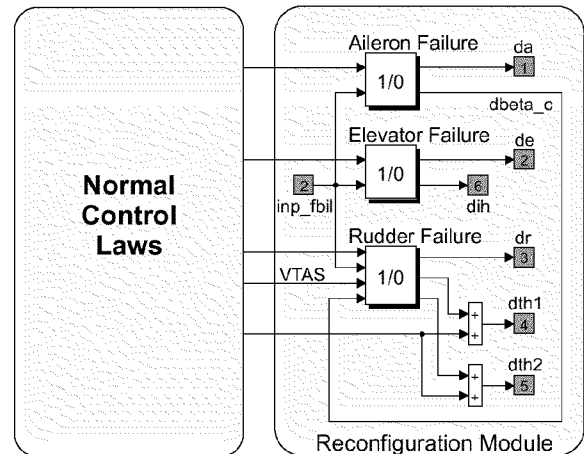


Fig. 16: Reconfiguration Module

The clear distinction between reconfiguration laws and normal control laws helps to investigate failure cases step by step and simplifies certification procedures. Furthermore, reconfiguration modes can be added automatically or by hand as an optional setting. Simulation runs for all segments of the mission were conducted in Matlab/Simulink for the normal landing as well as the landing with engines and stabiliser only. By and large, the aircraft stayed within the boundaries and landed safely even with substantial wind disturbances. Detailed results comparing the failure and the no-failure cases have been published in Ref. 25.

Considering the relatively simple reconfiguration module it can be concluded that the reconfiguration works well even under severe wind disturbances. However, it currently lacks the proof of suitability for additional envelope points or failures that had not been taken into account during the design. The reconfiguration approach depends on knowing in advance the attainable control forces and moments of the damaged aircraft and is not totally independent of the existing controller structure. The modularity still promises high applicability with low design risk. In order to prove the compatibility with other existing control systems the reconfiguration module has to be connected to a modern auto-pilot design capable of fulfilling normal design specifications and all certification requirements. Hence, the modular approach will be flight-tested on ATTAS in combination with the REAL autopilot design.

Education of test pilots

The education of high-level test pilots includes one important aspect: the flight-test. The students have to learn how to evaluate the dynamics of a given vehicle. Furthermore, they may have to pilot a large number of very different airplanes. The selection may include the whole bandwidth from glider to fighter, from amphibious fire-fighting aircraft to huge transport types. However, a flight-test school that has the high demand to provide all those aircraft types will have astronomical costs. Therefore, test-pilot schools have to find the most efficient and realistic way to meet this learning objective.

The in-flight simulation is a viable alternative and a good compromise to replicate different aircraft dynamics with a single airplane. The basic idea of in-flight simulation is to imprint the characteristics of a vehicle to be simulated on a fly-by-wire host aircraft. ATTAS' in-flight simulation capabilities were the reason for one of the most famous test-pilot schools, the French *Ecole du Personnel Navigant d'Essais et de Reception (E.P.N.E.R.)* to put DLR in charge of the non-linear in-flight simulation of a wide-body transport aircraft with a mass of about 130 tons. By this means the school was able to provide wide-body flight lessons to their students but had to pay only the operating costs of the small VFW 614.

The contract not only included the simulation of the wide-body but also the demonstration of effects caused by different flight control laws typically used on transport aircraft. Therefore, two more control laws were added to the existing rate command attitude hold (RCAH) system, an n_z law and an α law. Both laws were designed using Matlab/Simulink and transferred to ATTAS using Real-Time Workshop.

A pilot can only do a proper assessment if the task he has to perform adequately excites the aircraft dynamics. Two different tasks were offered to the test-pilot students:

- aggressive (high gain) tracking in the longitudinal and lateral-directional motion, similar to those described for the SCARLET 3 project
- approaches following an artificial (computer generated) Instrumental Landing System to a synthetic runway as well as visual approaches to a real runway combined with a simulated engine failure.

Some subtasks were also available. It was possible to deactivate the yaw damper or the turn compensation system, and a simulated turbulence model could be switched on in flight. After performing the task, the pilot had to make assessments in the form of general comments and Cooper/Harper Ratings.

As mentioned earlier, ground-based simulator sessions are part of the usual preparation phase for ATTAS experiments. The flight-tests for the test-pilot school E.P.N.E.R took place at Istres/France, where the ATTAS fixed-based simulator is not available. Therefore, a very sophisticated feature of ATTAS was used, namely the embedded ground-based simulation. The explicit model following system that is the basis of the ATTAS in-flight simulation²⁶ makes it possible to simulate the aircraft model in real-time. The ATTAS in-flight simulation software package includes the possibility to simulate the model while ATTAS is on the ground. Sitting in the cockpit like in flight, the evaluation pilot can control the model with the usual input devices (sidestick, pedals, throttles, etc.). The electronic flight instrument system (EFIS) indicates how the simulated model reacts. Using this ATTAS feature "familiarisation flights" were possible for the test-pilot students on the ground.

Figure 17 shows typical flight-test results using the n_z law. The bottom plot shows the commanded and the actual pitch attitude, the upper diagram depicts the pilot's sidestick pitch commands. It can be seen that a high activity is necessary to obtain an adequate result.

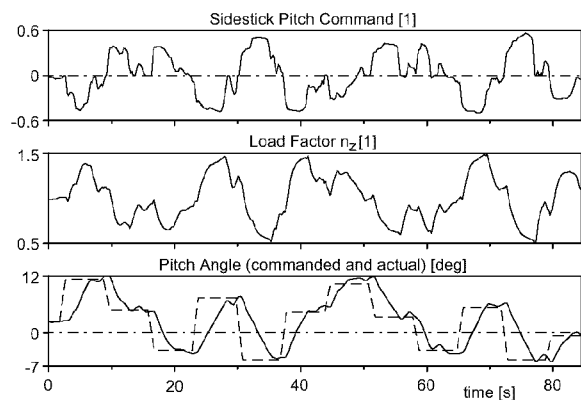


Fig. 17: Example from test-pilot training

Part of the education is an extended debriefing after the flight lesson. The test-pilot students, the ATTAS cockpit crew, flight-test engineer and the instructors of the school discussed results of the flight-test. DLR Institute of Flight Research aids those debriefings through a mobile data evaluation system. It consists of a high performance laptop computer (workstation class) and the DLR software package DIVA.²⁷

EPIAS

Active tactile information provided by inceptors is not only important for a realistic in-flight simulation (force-deflection representation) but also for improving situational awareness of the pilot by force-feedback of aircraft/system information. A unique active sidestick concept based on an electro-magnetic force loading principle (MAGSI)^{28,29} is under development at DLR's Institut für Flugsystemtechnik and the Department of Electrical Engineering of Technical University of Braunschweig (figure 18). This system is a key element in DLR's EPIAS research program (Enhanced Pilot Information by using Active Sidestick).

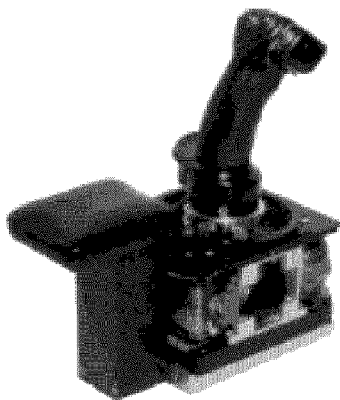


Fig. 18: MAGSI sidestick with integrated electro-magnetic actuator

The EPIAS research program is scheduled to be flight tested on ATTAS in 2000. The program is directed towards the following subjects:

- investigate the benefits on situational awareness in the case of sidestick cross coupling for a two men crew (for training purposes the instructor pilot can feel what the student pilot is doing, both pilots will feel if there are conflicting commands),
- examine the effects of providing the pilot with suitable tactile event and warning information on situational awareness (e.g. in case of leaving the flight envelope, stall warning, gear locked, etc.),
- determine which form of tactile excitation is suitable for what type of warning or event indication and also what type of excitation can be perceived and distinguished by the pilot (regarding frequency and amplitude),
- clarify if control force characteristics that are adapted to individual flight conditions can improve handling qualities and overall system performance,
- establish the optimal force characteristics for different aircraft classes,
- find out how situational awareness can be improved by moving the stick in accordance to autopilot commands, and finally
- study the influence of loss of active sidestick functions (feel system degradation to passive behaviour) on the controllability of the aircraft.

Conclusions

In this paper, several recent and current programs that examine different aspects of the development, optimisation and investigation of modern flight control systems have been described. In all these programs, flight testing using DLR's flying testbed ATTAS has played (and still plays) an important role. These projects, therefore, illustrate the variety of ways in which ATTAS can be used for ACT research.

References

- ¹Bauschat, J.-M., Lange, H.-H., "ATTAS and its contribution to System Design and In-Flight Simulation," Proceedings of the International Aircraft Flight Safety Conference, Zukovsky, 1993, pp. 3-44 to 3-56
- ²Buchholz, J.J., Bauschat, J.-M., Hahn, K.-U., and Pausder, H.-J., "ATTAS and ATTHes In-Flight Simulators," AGARD CP-577, Paper No. 31, May 1996
- ³Heintsch, T., Luckner, R., Hahn, K.-U., "Flight Testing of Manual Flight Control Functions for a Small Transport Aircraft (Project ATTAS-SAFIR)," AGARD CP-593, Paper No. 26, Sep. 1997
- ⁴Kröger, A., "Data flow oriented control law design with graphical language HOSTESS," Conference Proceedings, International Conference and Exhibition, 8th international event on Civil and Military Avionics, Heathrow, 1994
- ⁵Magni, J.-F., Bennani, S., Terlouw, J. (eds), "Robust Flight Control, A Design Challenge," Lecture Notes in Control and Information Sciences 224, GARTEUR, Springer Verlag 1997

- ⁶Joos, H.-D., "A methodology for multi-objective design assessment and flight control synthesis tuning," *Aerospace Science and Technology* Vol. 3, No. 3, pp. 161-176, Elsevier, Paris, April 1999
- ⁷Enns, D., Bugajski, D., Hendrick, R., Stein, G., "An Evolving Methodology for Flight Control Design," *AGARD Conference Proceedings 560: Active Control Technology: Applications and Lessons Learned*, pp. 7-1 -- 7-12, Turin, Italy, May 1994
- ⁸Lambregts, A.A., "Vertical Flight Path and Speed Control Autopilot Design Using Total Energy Principles," *AIAA Paper 83-2239CP*, August 1983
- ⁹Joint Aviation Authorities Committee, *Joint Aviation Requirements – All Weather Operations*, Printing and Publication Services Ltd, Cheltenham, England, 1996
- ¹⁰Moormann, D., Mosterman, P.J., Looye, G., "Object-oriented computational model building of aircraft flight dynamics and systems," *Aerospace Science and Technology* Vol. 3, No. 3, pp. 115-126, Elsevier, Paris, April 1999
- ¹¹McRuer, D.T., et al, "Aviation Safety And Pilot Control. Understanding and Preventing Unfavorable Pilot-Vehicle Interactions," *National Research Council, National Academy Press*, Washington, DC, 1997, p.15.
- ¹²McKay, K., "Summary of an AGARD Workshop on Pilot-Induced Oscillations," *AIAA Paper 94-3668*, Scottsdale, AZ, Aug. 1994
- ¹³Duda, H., "Flying Qualities Criteria Considering Rate Limiting", *DLR-FB 97-15*, Braunschweig, April 1997 (in German)
- ¹⁴Duda, H., "Prediction of Pilot-in-the-Loop Oscillations due to Rate Saturation," *Journal of Guidance, Control, and Dynamics*, Vol. 20, No. 3, 1997, pp. 581-587
- ¹⁵Duda, H., Duus, G., Hovmark, G., Forssell, L., "New Flight Simulator Experiments on PIO due to Rate Saturation," *AIAA Paper 98-4336*, Boston, MA, Aug. 1998
- ¹⁶Duda, H., Koehler, R., Fischenberg, D., "Analysis of Runway Steering PIO Incident of a modern Fighter Aircraft," *DLR-IB 111-98/27*, Braunschweig, Sep. 1998
- ¹⁷Duda, H., Duus, G., "New Handling Qualities Database on PIO due to Rate Saturation," *DLR-FB 97/53*, Braunschweig, Dec. 1997
- ¹⁸Rundqwist, L., Hillgren, R., "Phase Compensation of Rate Limiters in JAS39 Gripen," *AIAA Paper 96-3435*, San Diego, CA, Aug. 1996
- ¹⁹Kish, B.A., et al, "A Limited Flight Test Investigation of Pilot-Induced Oscillation due to Rate Limiting", *AIAA Paper 97-3703*, New Orleans, LA, Aug. 1997
- ²⁰Duus, G., "SCARLET 3 – A Flight Experiment Considering Rate Saturation," *AIAA Paper 2000-3987*, Denver, CO, Aug. 2000. (to be published)
- ²¹Buchholz, J.J., Heine, W., and Baumgarten, G., "Genetic Algorithms for Reconfiguration," *ZFW*, Vol. 20. No. 3., June 1996
- ²²Goldberg, D.E., "Genetic Algorithms in Search, Optimization, and Machine Learning," *Addison-Wesley*, 1989
- ²³Burcham Jr., F.W., Maine, T.A., and Burken, J.J., "Development and Flight Test of an Augmented Thrust-Only Flight Control System on an MD-11 Transport Airplane," *NASA Technical Memorandum 4745*, 1996
- ²⁴Lambrechts, P., Bennani, S., Looye, G., and Moormann, D., "The RCAM Design Challenge – Problem Description," in "Robust Flight Control: A Design Challenge," *Lecture Notes in Control and Information Sciences 224*, Editors: Magni, J.F., Bennani, S., and Terlouw, J., Springer-Verlag, London, 1997, pp. 149-179
- ²⁵Heine, W., "Alternative Flight Control Strategies For Multiple Effector Failures," *RTO-SCI Symposium on "Flight in a Hostile Environment"*, Solomons Island, MD, USA, 19-21 Oct. 1999
- ²⁶Bauschat, J.-M., "On the Application of a Nonlinear In-Flight Simulation Technique," *Proceedings of the First European Control Conference (ECC 91)*, Grenoble (France), Volume 73, July 1991, pp. 2415-2422
- ²⁷Wulf, G., Buchholz, J., "XDIVA - Anwendungshandbuch - 2. Auflage," *DLR IB111-97/26*, 1997 (in German)
- ²⁸Meins, J., Deeg, C., Hanke, D., Münscher, D., "Advanced Sidestick Controller with Electro-magnetic Loading System," 'Making it Real' *CEAS Symposium on Simulation Technology*, Delft, The Netherlands, Oct. 30 - Nov. 1. 1995
- ²⁹Hanke, D., Herbst, C., "Active sidestick technology - a means for improving situational awareness," *Aerospace Science and Technology*, 3 (1999), pp. 525-532